FINAL REPORT:

Space-Time Optical Systems for Ultrahigh-Speed Signal Processing and Encryption

DAAG55-98-0514
9/21/1998 – 3/20/2000

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REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	5-17-00	Final 9-21-98 --3-20-00

4. TITLE AND SUBTITLE
Space-Time Optical Systems for Ultrahigh-Speed Signal Processing and Encryption

5. FUNDING NUMBERS
DAAG55-98-1-0514

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(ES)
Purdue University
Division of Sponsored Programs
Hovde Hall
West Lafayette, IN 47907

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
ARO 38314.4-EL

11. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12a. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12 b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Our overall objective is to demonstrate powerful new signal processing funtionalities for ultrafast optical signals, with an emphasis on proof-of-concept experiments of new space-time optical processing methods for digital logic operations, especially encryption and temporal pattern matching, on ultrafast optical bit streams. During this project period we focused on an optical space-to-time converter, which is one of the key subsystems in the envisioned space-time optical processing system. For the first time we have worked out how the dispersion varies with the positions of the constituent optical components, and we have verified our analysis experimentally. Our results demonstrate a means for compensating or controlling the chirp of the optical pulse sequences generated from the space-to-time converter, which is important for subsequent transmission in optical networks. Furthermore, our work show the possibility of using these space-to-time converters for generation of identical pulse sequences at a series of different wavelengths, with potential application to optical networks and photonic processing. Finally, for the first time we demonstrated generation of terahertz rate trains of optical pulses using an integrated component, which increases the opportunity for practical applications.

14. SUBJECT TERMS
Optical Networks
Photonic Processing
Femtosecond Pulses
Pulse Shaping

15. NUMBER IF PAGES
10

16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Enclosure 1

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

I. Problem statement

Our overall objective is to demonstrate powerful new signal processing functionalities for ultrafast optical signals, with an emphasis on proof-of-concept experiments of new space-time optical processing methods for digital logic operations, especially encryption and temporal pattern matching, on ultrafast optical bit streams. The proposed space-time processing systems (see Fig. 1) consist of three subsystems: (1) a time-to-space converter for demultiplexing ultrafast TDM optical data, (2) a smart pixel device array for processing of the demultiplexed data, including digital logic operations suitable for encryption functionality, and (3) a space-to-time converter for generating an output pulse sequence corresponding to the processed or encrypted data. In this contract we focused on the optical space-to-time converter.

II. Summary of accomplishments

We had previously demonstrated femtosecond operation of a direct space-to-time (DST) pulse shaper, in which the output waveform or pulse sequence is a direct temporal replica of a spatial masking pattern [1]. This is in contrast to the widely used Fourier transform (FT) pulse shaper with a Fourier transform relationship between the masking pattern and the output temporal waveform [2]. In our previous experiments, however, the generated pulse sequences were chirped, which would be disadvantageous for subsequent transmission. Therefore, we investigated the dispersive properties of the space-time converter, with the aim of controlling the chirp.

The DST pulse shaper (Fig. 2) consists of a grating followed by a lens and a slit, with the grating and slit normally placed at the opposite focal planes of the lens. The input beam to the grating is spatially patterned, and the output temporal waveform after the slit is a directly scaled replica of the input spatial pattern. Although this configuration is itself dispersion-free, any phase curvature in the input beam results in a chirp in the output temporal signal. To compensate such chirps, we initially analyzed the effect of changing the lens-slit separation. Our analysis showed that variation of the lens-slit separation leads to a dispersion which can be adjusted to exactly compensate the dispersion arising from input phase curvature. Furthermore, we predicted that the output temporal intensity profile is completely unchanged as the chirp is varied in this way. We have confirmed both of these predictions experimentally (Fig. 3) [3]. It is interesting that our results are completely different than for the FT pulse shaper, where dispersion is controlled only by varying the lens-grating separation. This work was submitted to CLEO '99; our paper was accepted and upgraded to an invited talk.

We have extended this work by investigating the general case where both the grating-lens and lens-slit separations are varied independently. We have worked out a general formula which gives the dispersion as both separations are varied. Interestingly, we find that although the grating-lens separation does not affect the dispersion if the lens and slit are separated by exactly one focal length, in general the dispersion depends on both the grating-lens and lens-slit separations in a coupled way. This generalized dispersion formula has been verified experimentally [4].

We also investigated the effect of moving the slit transversely to the lens-slit axis and showed both theoretically and experimentally that this allows tuning the center wavelength while leaving the output intensity profile unchanged. This effect can be used to generate a series of identical pulse sequences at a variety of different wavelengths. This has application to hybrid wavelength-division multiplexed / time-division multiplexed optical networks as well as photonic processing systems, such as photonic A/D.

Finally, based on insights developed in the bulk optics DST pulse shaper research, we demonstrated for the first time that terahertz rate trains of ultrashort optical pulses can be generated with an integrated optic device called an arrayed waveguide grating (AWG) router (see Fig. 4). These devices are commonly used for wavelength-division multiplexed optical communications, but had never previously been applied for generation of ultrashort time-domain pulses at terahertz rates. As in the DST pulse shaper, different output ports of the AWG router produce pulse trains which are wavelength shifted but otherwise identical. This work using an integrated optic component increases the opportunities for practical implementation of our pulse train generation scheme while identifying a new functionality for the AWG technology.

The overall significance of our work during this period is as follows:

(1) We now have a means of controlling the chirp in the DST pulse shaper, which ultimately is needed to make the output from the proposed space-time processing systems compatible with optical networks.

(2) The dependence of the dispersion on the position of the optical components is completely different than in the widely used FT pulse shaper; therefore, our results offer new vistas for dispersion control in ultrafast optics.

(3) We have identified at least one functionality of the DST pulse shaper which can be reduced to an integrated format, which enhances the opportunities for practical application. At the same time, we have invented a new method for generation of identical wavelength shifted versions of extremely high rate optical pulse trains, with potential applications both to optical networks and photonic signal processing.

Recognition of our work by the technical community is evidenced through a number of awards and invited talks. Lists of publications, awards, invited talks, and invited seminars are given as appendixes.

III. References

[1] D.E. Leaird and A.M. Weiner, "Femtosecond Optical Packet Generation via a Direct Space-to-Time Pulse Shaper,"Opt. Lett. **24**, 853-855 (1999).

[2] A.M. Weiner, "Femtosecond optical pulse shaping and processing,"Prog. Quantum Electron. **19** (3), 161-238 (1995).

[3] D.E. Leaird and A.M. Weiner, "Chirp control in the direct space-to-time pulse shaper,"Opt. Lett. (to appear, June, 2000).

[4] D.E. Leaird and A.M. Weiner, "Femtosecond Direct Space-to-Time Pulse Shaping," (in preparation).

IV. Scientific personnel

1. Prof. A.M. Weiner (principal investigator)
2. D.E. Leaird (research engineer and Ph.D. student)
3. Shuai Shen (Ph.D student)
4. Peter Rakich (undergraduate)
5. Muhammed Zakir (undergraduate)

V. Inventions

1. "Direct Space to Time Pulse Shaper"
   (provisional patent application filed)

2. "Optical Pulse Train Generator"
   (provisional patent application filed)

Appendix A: List of awards

- A.M. Weiner was awarded the **IEEE Lasers and Electro-Optics Society (LEOS) William Streifer Scientific Achievement Award** for "pioneering contributions to femtosecond optical pulse shaping technology and its applications."

- Dan Leaird was awarded the **1999 New Focus Student Award from the Optical Society of America (OSA).**

- A.M. Weiner received a **Humboldt Research Prize for Senior U.S. Scientists** from the Alexander von Humboldt Foundation.

- A.M. Weiner was named recipient of the 1997 ICO Prize from the International Commission for Optics. The prize was awarded at General Meeting of the International Commission for Optics in San Francisco, CA, August 2-6, 1999.

Appendix B: Publications

1. D.E. Leaird and A.M. Weiner, "Femtosecond optical packet generation via a direct space-to-time converter," Optics Letters **24**, 853-855 (1999).

2. D.E. Leaird and A.M. Weiner, "Chirp control in the direct space-to-time pulse shaper," Optics Letters, to appear, June, 2000.

3. D.E. Leaird and A.M. Weiner, "Femtosecond Direct Space-to-Time Pulse Shaping," in preparation.

4. D.E. Leaird and A.M. Weiner, "Generation of Femtosecond Optical Pulse Sequences from a Direct Space-to-Time Pulse Shaper," in Ultrafast Optics and Optoelectronics 1999, J. Bowers and W. Knox, editors, Optical Society of America, Trends in Optics and Photonics (TOPS) , vol. 28, pp. 63-69.

5. A.M. Weiner, "Femtosecond Pulse Shaping Using Spatial Light Modulators," **[INVITED REVIEW ARTICLE]**, Review of Scientific Instruments, to appear, May, 2000.

6. A.M. Weiner, "Femtosecond Pulse Processing, " **[INVITED]**, Optics and Quantum Electronics **32**, Special Issue on Ultrafast Optoelectronics, to appear.

Appendix C: List of invited talks

1. "Femtosecond Pulse Processing," A.M. Weiner, International Photonics Conference, Taipei, Taiwan, Dec. 15-18, 1998.

2. "Fourier optics femtosecond pulse processing," A.M. Weiner, Optics in Computing, Snowmass, CO, April 12-16, 1999.

3. "Chirp compensation in a femtosecond direct space-to-time optical pulse shaper," D.E. Leaird and A.M. Weiner, Conference on Lasers and Electro-optics (CLEO), Baltimore, MD, May 24-28, 1999.

4. "Femtosecond Pulse Processing", A. M. Weiner, 1999 General Meeting of the International Commission on Optics, San Francisco, CA, Aug. 2-6, 1999.

5. "Femtosecond second harmonic generation in thick nonlinear crystals with applications to ultrafast signal processing," A. M. Weiner, Center for Nonlinear Optics Materials Meeting, Stanford University, Sept. 23-25, 1999.

6. "Femtosecond Pulse Processing for Applications in Broadband Optical Communications," A. M. Weiner, IEEE LEOS Annual Meeting, San Francisco, CA, Nov. 8-11, 1999.

Appendix D: List of invited seminars

1. "Femtosecond Pulse Processing and Applications to Optical Communications," A.M. Weiner, Bell Labs-Lucent, Murray Hill, NJ, Jan. 19, 1999.

2. "Hyperspectral Processing of Femtosecond Pulses (with Applications to Hyperspectral Sensing,)" Defense Sciences Research Council Workshop on Multispectral Automatic Target Detection/Recognition, Arlington, VA June 2, 1999.

3. "Femtosecond Pulse Processing and Applications," A.M. Weiner, Max Born Institute, Berlin, Germany, Nov. 22,1999.

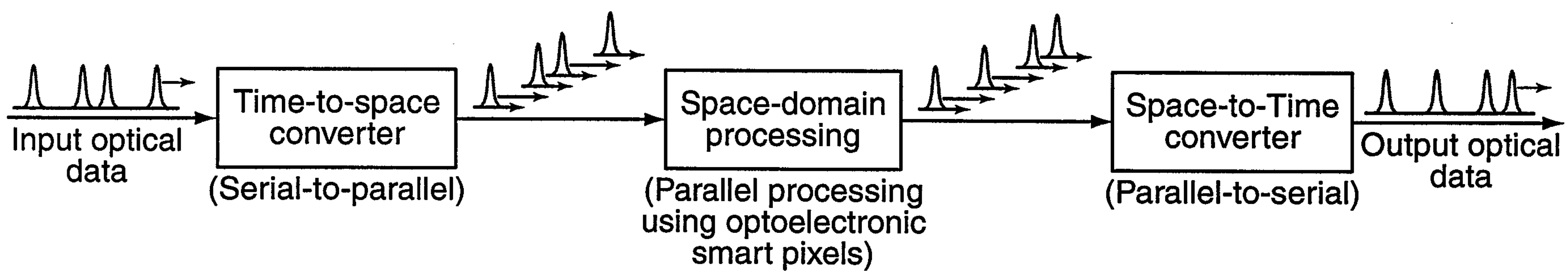
4. "Selected Research from the Purdue University Ultrafast Optics and Fiber Communications Laboratory," A.M. Weiner, Freie Universitaet, Physics Department, Berlin, Germany, Nov. 24, 1999.

5. "Femtosecond Pulse Processing and Applications," A.M. Weiner, University of Karlsruhe, Electrical Engineering Department, Karlsruhe, Germany, Dec. 3, 1999.

6. "Femtosecond Pulse Shaping and Selected Applications in High-Speed Information Processing and Generation of Terahertz Radiation," A.M. Weiner, Berlin Femtochemistry Research Consortium, Freie University, Berlin, Germany, Dec. 14, 1999.

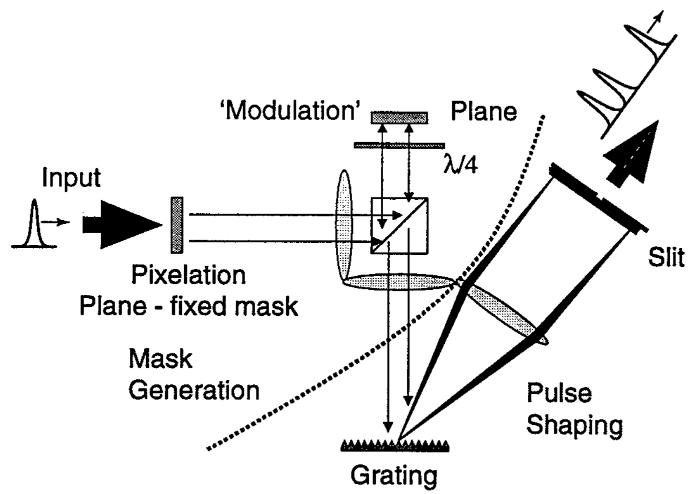
7. A.M. Weiner, "Femtosecond Pulse Processing with Applications to Broadband Optical Communications," A.M. Weiner, Heinrich Hertz Institute for Communications Technologies, Berlin, Germany, Jan. 13, 2000.

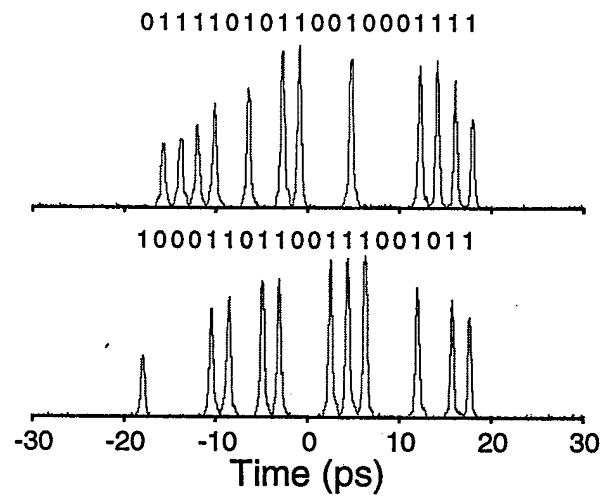
Space-Time Optical Systems for Ultrahigh-Speed Signal Processing and Encryption



- Space-time optical systems offer a new approach for processing of ultrahigh-speed optical data, with applications to encryption and temporal pattern matching.
- We have focused on the parallel-to-serial converter subsystem, with the following key results:
    - generation of subpicosecond optical pulse sequences via direct space-to-time conversion in both bulk optics and integrated implementations
    - first investigation of the dispersive properties of the direct space-to-time apparatus

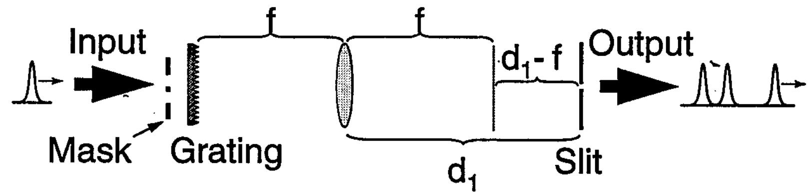
Direct Space-to-Time Pulse Shaper for Ultrafast Optical Parallel-to-Serial Conversion

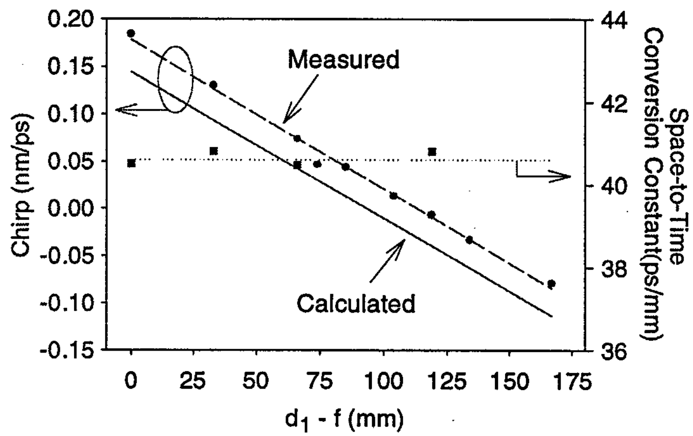


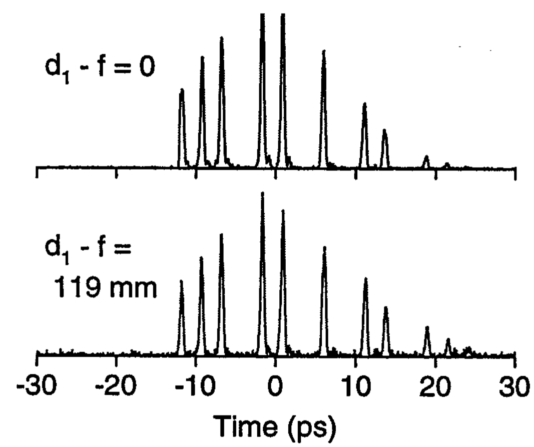


- Performs parallel to ultrafast optical serial conversion, generating waveforms which are directly scaled replicas of a spatially patterned input beam on grating.
- By placing fixed spatially patterned masks at the 'pixelation plane', subpicosecond optical pulse sequences have been generated with high on-off contrast.
- Direct space-to-time conversion facilitates the use of optoelectronic modulator arrays, which will be placed at the 'modulation plane' in future experiments for pulse sequence generation with nanosecond reprogramming times.

Dispersion Control in Direct Space-to-Time Pulse Shapers

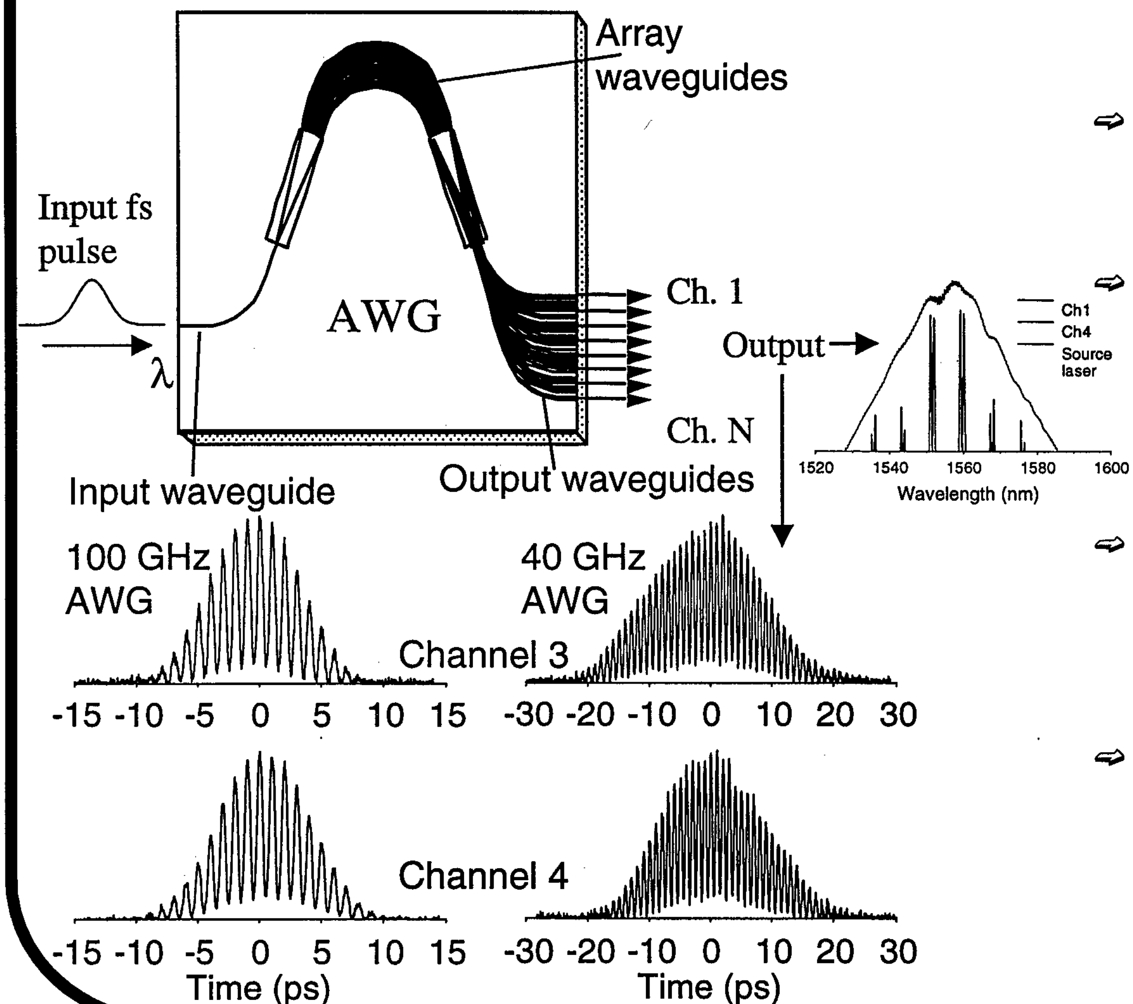






- First analysis of the dispersion properties of the direct space-to-time pulse shaper.
- Confirmation that the output chirp can be tuned through zero by adjusting the lens-slit separation (important for subsequent transmission), while the space-to-time conversion constant and the output intensity profile remain unchanged.
- Analysis extended to include variations in both lens-slit and grating-lens separation, with experimental verification in progress.
- Because the variation of the dispersion is completely different than in the widely used Fourier transform pulse shaper, our results offer new vistas for dispersion control in ultrafast optics.

THz Rate Pulse Train Generation



- THz rate trains generated **simultaneously at multiple wavelengths**
- First integrated implementation of bulk optics direct space-to-time pulse shaper previously developed at Purdue
- Potential for continuous THz-rate trains, ON-OFF modulated pulse sequences, sub-ns reprogramming
- Applications: hybrid WDM-TDM, photonic signal processing

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supported in part by ARO under DAAG55-98-1-0514